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Adoption of Aviation-Derivative Engines for Use As Part of a Power Unit of High Capacity

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Abstract—Possible ways of adopting aircraft-engine derivative gas turbines for their implementation in power units of high capacity are considered.

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Until recently, manufacture of gas-turbine engines in Russia was mainly oriented for their use in aircraft and shipbuilding. Only some design offices and manufacturers of gas turbines (GTEs) supplied their production to civil industry. At present, most of these enterprises in Russia have begun to develop power units and drives for gas-pumping plants [1]. Using their comprehensive design and technological experience, they intend, first of all, to expand the range of application of GTEs that are presently manufactured or repaired at these enterprises. Upgrading of aircraft or marine GTEs (hereinafter, both types of engines will be referred to as aircraft) for their further application as the drives of gas-pumping devices or electric turbogenerators mainly relates to combustion chambers (CCs).

It is apparent that the entire spectrum of works on modernization of CCs and the aircraft-engine derivative GTEs as a whole is rather wide. A list of additional works depends on the conditions of the engine operation. For the engines to be used in power engineering, the primary requirements are as follows: a high efficiency, a lifetime of 100000 h or more, and environmental friendliness. Under conditions of strong competition, these installations should have a low cost, a high maintainability, and minimum expenditures for servicing. They should be reliable as well. While improving the design of GTEs, the requirements of minimizing their overall dimensions and mass should also be accounted for.

We should note that aircraft-derivative engines retain certain features typical of their prototypes, i.e., limited air flowrate through a compressor (and limited unit power as a consequence); a high frequency of the rotor rotation, as a rule; multishaft design; and the like. Radical changes in the engine scheme and design require great investments in the technological base of the manufacturers, which is impossible under current conditions. However, modern technologies of manufacturing the units and articles having ultracomplex configurations with intense cooling systems, application of monocrystal casting and composite materials, high-temperature soldering, multilayer coatings, etc. make it possible to a considerable extent to counterbalance the above limitations in the prototype engines and create units and articles that can operate under conditions that are unusually hard for traditional power engineering. In addition, aircraft-engine building works have accumulated experience in mastering and rearranging mass production processes.

An aircraft-engine derivative gas-turbine designer should be able to use modern means of designing and finishing the objects to be manufactured. This makes it possible that a comprehensive solution to the problem of modernization of CCs and other items of the engine will be found in a short time with minimum field testing of the articles and the unit as a whole. Use of the advanced information technologies and their application in the modern automated manufacturing process is a necessary condition for success.

One such information system is the continuous acquisition and life-cycle support technology (CALS technology), which was introduced in 2000 at the Moscow Salyut Machine-Building Enterprise (Salyut MMPP) with subsystems for automated calculating and managing of the design during all of its phases and a subsystem for preparation of electronic carriers for accompanying the manufacturing and testing of the articles and units. The use of this system made it possible to develop in a short time the CC of the MES-60 combined-cycle installation with steam injection into a CC for the power industry, to retrofit the CC of the GTE-20 gas turbine (for the power plant in the city of Yamburg) and provide a changeover to a different type of fuel, to develop a highly maneuverable and efficient CC of 2.4-MW heat capacity for locomotives, and to create other types of aircraft-engine derivative gas turbines. The good effectiveness of this activity was determined by the information integrity and continuity at all of the phases of the CC life cycle from the beginning of the design process until introduction of the object into mass production with subsequent monitoring of its operation and servicing. The latter are the mandatory

factors of operation of modern power engineering units.

While upgrading the CC of an aircraft engine to provide implementation of the latter as a drive that operates exclusively with gaseous fuel, a set of obligatory measures must be accomplished in addition to the traditional replacing of the liquid-fuel supply system by the gaseous-fuel one. These measures include modernization of the combustor's liner (the burners and the systems of CC cooling and combustion-products dilution are to be reconstructed).

When reconstructing CC burners, the following problems must be solved. First of all, the main shortcoming of the original aircraft engine, i.e., the emission of harmful substances that does not meet current standards, should be eliminated. To reduce NO_x emissions, a developer usually tries to decrease the temperature in the CC combustion zone (in the flame) below 1600°C and reduce the hot-gases' residence time at high temperatures. Such an attempt often leads to a decrease in the reliability of the engine start-up and to deterioration of the fuel combustion completeness. In practice, there have been cases in which the modernization of the original CC aimed at the reducing of the flame temperature led to failure of the engine, which had earlier stably operated in a wide range of air excess, because of the incipience of the vibration burning in the CC or due to a considerable nonuniformity of the gas-temperature field in the CC and at the turbine inlet. Second, while being used in electricity-generating installations, a gas-turbine engine must be able to provide essentially instantaneous transition from the rated regime of the electric-generator operation to the no-load run. Meeting such a requirement is necessary to provide the possibility of repetitive switching-on of the power unit in the case of its emergency switching-off by external protection devices. Taking into account of the compressor inertia, there are several methods to quickly reduce the power produced in the gas generator that speed up the power turbine. One of these methods is the reduction of the fuel flowrate to the combustion chamber. This is a rather difficult task, because in the course of its implementation we violate optimum parameters of the fuel–air mixture in the combustion zone of the combustor, which provides stable burning. In other words, the CC must have very high operating characteristics in terms of "lean flame-out," which are hardly attainable due to a decrease in the flame temperature in a combustor liner.

Thus, the development of CCs that meet the requirements regarding the completeness of the combustion process, the operation stability, the temperature-field uniformity, and the minimum pressure losses is a very complicated problem. The experience gained by the design bureaus of the Salyut MMPP and the Mashproekt enterprise (Nikolaev) showed that the development and mastering of a low-toxicity CC operating with a lean homogenized fuel–air mixture require much greater expenditures than those necessary for the development of a low-toxicity CC with NO_x suppression by steam admixing to the combustion zone. The difference in the expenses can reach several tens or even hundreds of times. Therefore, if we have steam at a power plant, the possibility of using it in aircraft-engine derivative gas turbines to meet requirements for environment protection should certainly be considered.

While reconstructing an aircraft engine, in addition to the CC, the following engine articles are to be changed as well: bearings, the compressor guide-vanes control system, etc. Certain less labor-intensive tasks are to be solved as well.

In addition to the above technological characteristics that provide meeting the environmental, reliability, and maintainability requirements, an aircraft-engine derivative installation must have a low cost of electricity production (acceptable payback time) and have unit capacity that is as large as possible. The latter requirement is very important if the installation is intended to be used in a power system or replace equipment in operation in the Russian power system (gas turbines for independent energy sources, small boiler-house toppings, or mini cogeneration plants can have a smaller capacity).

For the entire life cycle of the installation, we can write the following correlation:

$$P = G_{\mathrm{el}} + G_{\mathrm{ht}} + G_{\mathrm{th}} - C_{\mathrm{GTU}} - C_{\mathrm{op}} - F - A, \qquad (1)$$

where P is the profit obtained during the entire life time of the installation; G_{el}, G_{ht}, and G_{th} are the gains obtained due to selling of electricity, heat, and mechanical or other kind of produced energy; C_{GTU} is the cost of buildings, technological equipment, assembling, and constructing of the installation with an account of the loan discount; C_{op} is the expenditures for servicing the installation, including wages, overhauls, and consumable materials; F is the cost of the fuel spent; and A is taxes, penalties, and other expenditures during the GTU operation life.

The maximum value of P is reached when the GTU used has its maximum thermal efficiency and minimum specific capital outlay. Under conditions of limited air flowrate through the prototype aircraft gas turbine, the latter condition is to a considerable extent determined by the specific capacity of an installation built on the basis of this prototype.

The thermal efficiency of a gas turbine engine depends on many factors. The decisive one is the ratio of the gas temperatures at the turbine inlet T_3 and at the outlet from it T_4 (or at the inlet to the compressor T_1). The installation has maximum efficiency with a certain combination of π_c and T_3, i.e., with a given gas temperature upstream of the turbine T_3, the maximum value of the efficiency is achieved at a certain corresponding compression ratio π_c,

$$\eta_t = f(\pi_c;\ T_3/T_1). \qquad (2)$$

An analysis of formula (2) shows that the air temperature upstream of the compressor produces a greater effect on the thermal efficiency of the installation than the gas temperature upstream of the turbine. A strong dependence of the installation specific power on temperature T_1 has been revealed also [2]. Therefore, to reach high economic indexes and retain the rated power at a high temperature of the ambient air, power installations are often equipped with devices that enable reduction of T_1. To cool the air at the inlet to the GTU compressor, different contact-type water-evaporation systems are applied, along with cold accumulators and refrigerating units.

A decrease in T_1 leads to a decrease in the temperature downstream of the compressor T_2, which, in turn, changes the conditions of CC operation, as does the presence of a certain amount of water vapor in the air. When using diffusion-type burners, a decrease in the air temperature at the inlet to the CC reduces NO_x emissions. For example, according to experimental data from the Salyut MMPP, if we do not introduce any changes in the design of the CC of a prototypic aircraft engine having elevated emissions of harmful substances, the injection of the atomized water at the inlet to the compressor in an amount of 1% of the air flowrate through the compressor can reduce NO_x emission by approximately twofold. In so doing, CO emissions will not be increased, while the liner casing and the burners themselves will operate under more favorable conditions due to an increase in the cooling system efficiency because of the reduction of T_2.

A more rational, staged water, injection into the compressor flow path gives the same results. We note that a decrease in the compression work in the compressor takes place not only because of cooling of the air due to water evaporation; there is another considerable factor. Aircraft-engine derivative gas turbines have rather high radial clearances between the compressor's rotor and stator, the existence of which is caused by the specifics of their operation (these clearances are necessary to provide the possibility of a sharp increase in the engine load and compensate for different temperature expansions of the rotor and the stator, as well as the distortion of the rotor due to gyroscopic effect during changes in the direction of an aircraft motion). Large radial clearances, however, reduce the compressor efficiency. This is especially true for the last stages of the compressor, where the blades' height is relatively small. The use of an aircraft engine under stationary ground conditions cancels the need for large radial clearances.

The radial clearance above the working blades decreases if the compressor casing is cooled by water separated on its surface in the case of the use of staged water injection [3].

One very important factor that should be accounted for in the case of water injection in the compressor is the possibility of water reaching the CC. This is a detrimental phenomenon as regards engine efficiency, reliability, and lifetime (with the exception of certain special cases). Fuel expenses in water evaporation in a CC are not warranted by the work done by the steam formed in the CC. Considerable temperature gradients, which appear due to direct impact of the water droplets on the incandescent liner, can cause its premature destruction. Therefore, the amount of water delivered to the compressor must be accurately metered. This amount depends not only on the location of the point of water injection and the temperature of the ambient air, but on the fineness of the water dispersion as well.

Assessments conducted at the Salyut MMPP showed the desired dimensions of the water droplets at the inlet to the compressor having a high frequency of rotation should be not more than 5 μm. Droplets of such a small size follow the air flow in the channels between the blades, only slightly separate on the blades, and cannot cause considerable erosion, which is observed under the impact of the droplets of the greater size. It follows from the calculations of the water droplet heat transfer in the carrying air flow that, with air velocities typical of the compressor, the water-droplet residence time in the compressor flow path is insufficient for its complete evaporation. With water injection in an amount of 1% of the air flowrate through the compressor, up to 80% of the water injected is evaporated, while with an increase in the water injection the share of the evaporated water decreases. In the course of experiments conducted at the TsIAM and the Salyut MMPP, it was recognized that, in the compressor tested, due to water separation on the blades and the casing, no water exists in the airflow at a distance of from three to five stages downstream of the point of water injection. The results of experiments with different degrees of heating of the water injected showed that the water temperature slightly effects droplet evaporation. Therefore, to solve the problem and exclude entering of a considerable amount of water into the CC while cooling the compressor casing by a separating moisture, it is, it seems, expedient to terminate the amount of water injected into the compressor by a value of 1.0–1.5% of the air flowrate and to accomplish this injection not earlier than downstream of the fifth stage.

Modernization of the aircraft engine under the condition of minimum expenses suggests minimum changes in the engine design. Of the three main parts of a gas turbine unit, i.e., the compressor, CC, and turbine, the latter requires the greatest expenses in its manufacturing (although, in total, the expenses for designing and working-up to the rated parameters of the pilot examples of the compressor and CC are not less than those for the turbine). An increase in the parameters of the aircraft-engine derivative gas turbine by means of a raise in the gas temperature upstream of the turbine suggests carrying out considerable changes in its design, that is, a high cost of modernization is anticipated. Due to these reasons, this route seems unacceptable. In addition, a considerable increase in the lifetime

of the gas turbines for power engineering is presently provided by reducing the working temperatures T_3 implemented in the aircraft gas-turbine engine. It follows from this that, economically speaking, the use of aircraft GTEs with reduced gas parameters upstream of the turbine is justified only under certain conditions. In the general case, a decrease in the efficiency due to reducing T_3 must be counterbalanced by measures that make the cycle more complex. These measures are as follows:

(i) the use of intermediate heating of the gas in the second CC installed between the turbine stages,

(ii) transferring of the waste-gases' heat to the air entering the CC, and

(iii) the use of combined-cycle (steam–gas) technology.

The use of gas-turbine engines in cogeneration installations with prevailing heat supply to external users is not considered in our paper.

The two first alternatives of GTE modernization are connected with considerable capital expenses. To create GTUs with intermediate heating of the working gas or waste-gases' heat regeneration, which would have a thermodynamic efficiency of 40–42%, it is necessary to manufacture a considerable amount of expensive turbine and CC articles (under certain conditions, such upgrading of a GTE is economically justified). To combine maximum effect with minimum expenditures, it is promising to use GTEs in combined-cycle installations (CCIs). Below, we will consider this problem in detail.

The specifics of any combined cycle is a combination of cycles with several working fluids. In a CCI, the working fluids are water (steam) and air (combustion products). In a steam-turbine power cycle, the air and the combustion products of a fuel are only a heating medium for the water and steam, while in a combined cycle this steam, along with the combustion products, produces useful work. There are two main kinds of combined-cycle installations:

(i) binary CCIs with discharge of GTE combustion products into the heat-recovery boiler (HRB), where the steam for the steam-turbine cycle is generated and

(ii) with discharge of GTE waste gases to the boiler, where the steam to be injected into the gas turbine is generated.

Binary-type CCIs are most widely used. Their thermal efficiency is 51–59%, with the thermal efficiency of the GTE itself being 36–41%. These indexes are reached with a temperature T_3 = 1350–1520°C. For such installations, calculations according to (2) give less optimum values of π_c at given T_3 as compared to the cases of simple GTU cycles. In the binary-type CCI, the power of the steam turbine constitutes 25–30% of the total CCI power. For the newest binary-type CCIs with two combustion chambers, the value of the CCI efficiency can reach 60% or even more. The assessments of the efficiency of using aircraft-engine derivative GTEs in a binary-type installation show, however, that the efficiency of such CCIs will be considerably lower than that for the best modern installations (due to lower values of T_3). For example, the use of a shipborne DI-59 gas turbine engine with $T_3 \approx 1000$°C gives a CCI efficiency of 41–42%.

Aircraft-engine derivative binary-type CCIs have relatively small values of a specific power. At the same time, the composition of the main equipment at such CCIs is rather large. Therefore, the specific cost of such installations is high. It is possible to reduce the expenses by incorporating a gas-turbine engine with an existing steam-turbine installation (as its topping). However, the list of the engines that can be used for such toppings appears to be rather small.

In binary-type CCIs constructed on the basis of aircraft-derivative GTEs, the problem of emissions of harmful substances has also not been solved. Reducing these emissions down to the current standards for power-engineering combustion chambers without introducing steam into the combustion zone requires great expenditures. The reduction of NO_x emissions in binary-type CCIs by means of steam injection (so-called "environmental steam" injection) is possible if we simultaneously increase the flowrate of the HRB make-up water. The necessary amount of steam to be injected depends on many factors: the pressure and the temperature of the air upstream of CC, the air humidity, the air excess in the burners themselves and in the primary zone of the CC liner, the method of the flame stabilization applied, the arrangement of the cooling system, the residence time of the gas in the primary zone, and the injected steam temperature.

In combustion chambers, the steam delivery to the combustion zone prevents NO_x formation. In most of cases, the flowrate of the "environmental" steam depends on the fuel flowrate

$$G_{\mathrm{en.st}} = (0.5\ldots1.0)G_{\mathrm{f}}, \quad (3)$$

where $G_{\mathrm{en.st}}$ and G_{f} are the flowrates of the "environmental" steam and the fuel, respectively.

The experience gained with the operation of the Vodolei unit [4] has confirmed correlation (3).

The steam flowrate should not be controlled in the entire range of the unit power. The "environmental" steam is introduced into the CC at a high power of the GTE, usually starting from 50% of the rated power.

When wet steam is introduced into the GTE combustion chamber, the amount of "environmental" steam decreases sharply. It is also necessary to make the requirements for feedwater quality more rigid, because the presence of different-type admixtures in this water is fraught with the appearance of damages to the CC and GTE due to clogging steam atomizers, forming solid deposits of substances dissolved in the water on the CC and GTE surfaces.

The methods of introducing a large amount of steam into CCs and technological schemes of the water bal-

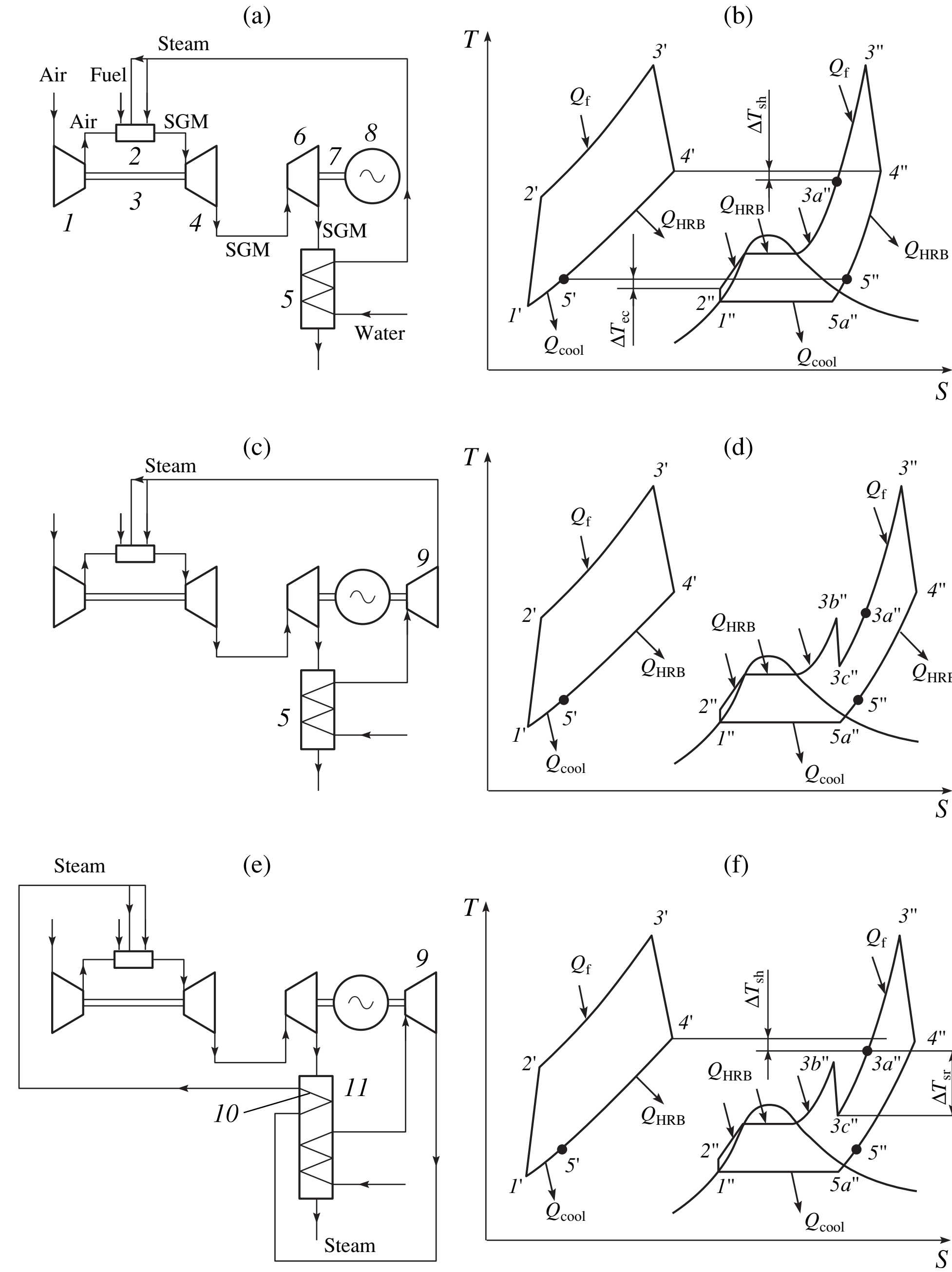

Fig. 1. Principal schemes (a, c, e, g, and i) and cycles (b, d, f, h, and j) with steam injection in the combustion chamber of a GTE. (*1*) Compressor; (*2*) combustion chamber; (*3*) transmission of the gas-generator turbine-driven compressor; (*4*) gas-generator turbine; (*5*) HRB; (*6*) power turbine; (*7*) turbogenerator transmission; (*8*) turbogenerator; (*9*) steam turbine; (*10*) intermediate steam reheater; (*11*) two-pressure HRB; (*12*) reburning combustion chamber; (*13*) cooler–condenser; (*14*) exhaust-gases compressor; (*15*) feedwater pump: SGM—steam-gas mixture, Q_f—heat delivered to the combustion chamber, Q_{cool}—heat removed to the cooler, Q_{HRB}—heat delivered to (removed from) HRB, ΔT_{ec}—temperature difference between the media in the HRB economizer, ΔT_{sh}—temperature difference between the media in the HRB steam superheater, ΔT_{sr}—the difference between the steam temperatures at the outlet from and the inlet to the steam reheater, ΔT_3—the difference between the gas temperatures upstream of the gas-generator gas turbine and upstream of the power turbine, Q_{rcc}—heat delivered in the reburning combustion chamber, $Q_{cl\text{-}cd}$—heat removed to the cooler–condenser.

ance provision in CCIs are most thoroughly developed for CCIs with steam injection into the combustion chamber. These installations seem to be preferable when aircraft-engine derivative GTUs are used. Below, such installations are considered in detail.

The simplest of the known schemes of such a type is the scheme given in Fig. 1a. This CCI operates as a simple-cycle GTU with certain distinguishing features. Waste-gas heat recovery is accomplished by means of an HRB as in the case of binary-type CCIs. Then, the

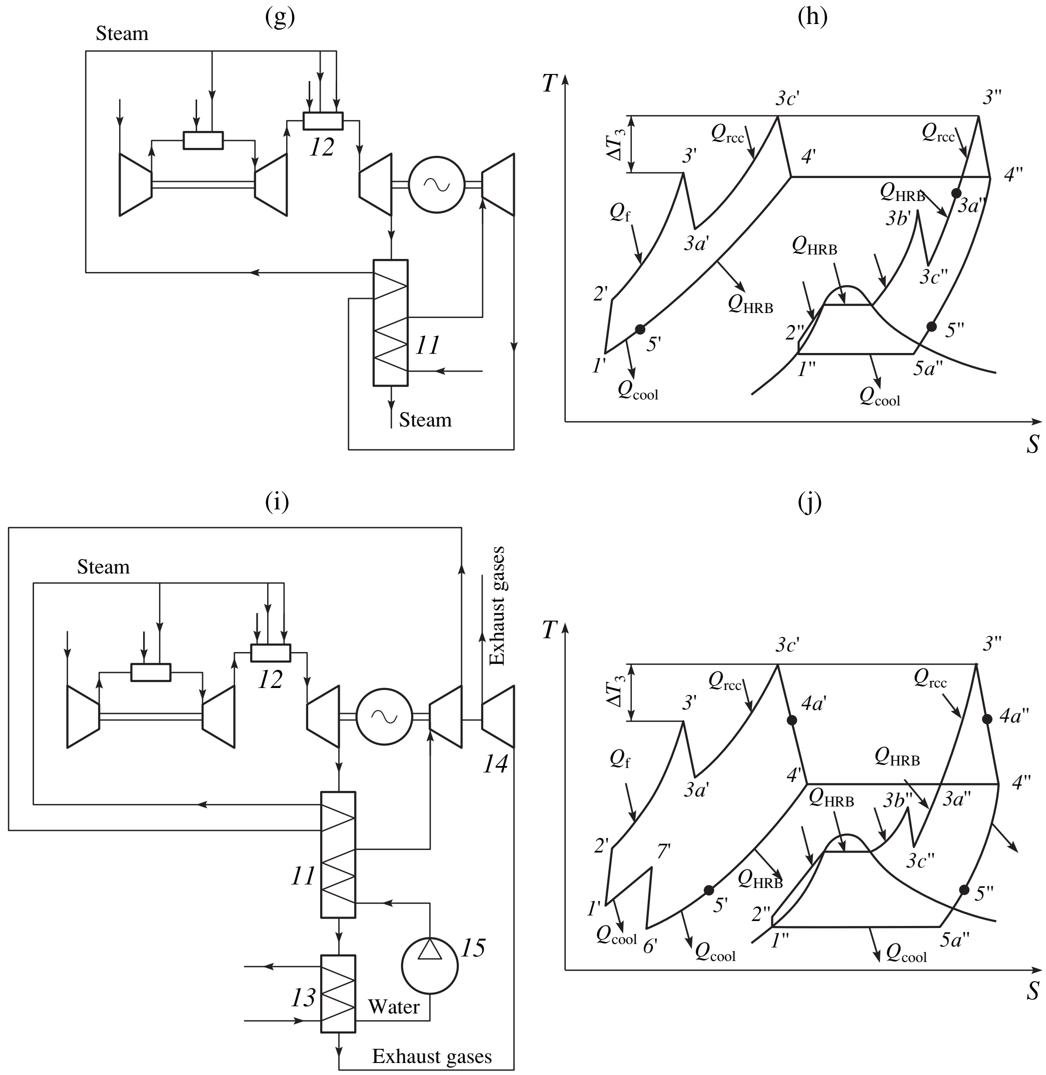

Fig. 1. Contd.

heat is returned into the cycle by means of steam delivery into the GTE. It is possible to accomplish this steam injection at different points of the cycle path. First, let us consider steam injection into a CC. Figure 1b shows the direct irreversible thermodynamic Brayton and Rankine cycles, which demonstrate the operation of the CCI under consideration. The air is heated in the CC by combusting fuel in it. The chemical reaction of burning of different kinds of fuel (including natural gas, kerosene, and diesel fuel) culminates in obtaining gas that mainly consists of nitrogen, oxygen, carbon dioxide, and steam. The amount of steam is not large; however, from several hydrocarbons, for example, from methane, we obtain a 2.26-fold mass of steam as compared to that of the fuel burned.

Some amount of the steam (water vapor) enters the CC with wet air, but a considerably larger part is inserted from the HRB of the installation under consideration. The amount of the latter can reach up to 25–30% of the air flowrate to CC. The heating of steam in CC (line *3a"–3"*) can be accomplished in several ways. Part of the steam is delivered immediately to the combustion zone to reduce NO_x emissions. The amount of the "environmental" steam $G_{en.st}$ necessary in this cycle is considerably higher than that in the binary cycle (calculated according to (3)). This is due to a higher amount of fuel burned G_f. In addition, in the CCI (see Fig. 1a), the use of steam instead of air as a turbine-blade coolant makes it possible to retain high values of T_3 upstream of the turbine and, correspondingly, high values of π_c. Due to burning a greater amount of fuel, which is caused by a necessity to heat the steam entering from the HRB to the temperature T_3, leads to a certain decrease in the air-excess coefficient value. The decrease in the amount of the excess air in a CC makes the combustion process closer to stoichiometric. This also causes an increase in the $G_{en.st}$ value (by 1.5–2 times) as compared to that obtained according to (3).

For emergency cases or a fast drop in power, the steam delivery system must be equipped with an antiaccelaration quick-response cutoff emergency valve. Strict controlling of the required amount of $G_{en.st}$ in accordance with the fuel consumption G_f is provided by the control valve. When reconstructing an aircraft engine, liquid-fuel atomizers are modernized for the use of natural gas; this is done simultaneously with arranging of the channels for "environmental" steam insertion.

Steam delivery to a CC can be accomplished through a system of the liners' cooling as well. In this case, the amount of steam to a great extent depends on the arrangement of this system and the heat intensity of the CC.

Part of the steam that is heated in CC is called "power steam." To reduce the temperature of the hot gases entering from the combustion zone to T_3, this "power steam" is injected immediately downstream of the combustion zone. The main conditions for this process are the absence of unburned fuel and formation of the required temperature field of the steam–gas mixture upstream of the turbine.

We should also point out that steam delivery to a CC is accompanied by an increase in the pressure in it because the flow paths of the compressor, the CC, and the turbine of the aircraft-derivative engine to be used were designed in accordance with the continuity law

$$G_\Sigma \sqrt{T}/p = \text{const}, \qquad (4)$$

where G_Σ is the total flowrate of the working fluid in the given element of the simple GTE cycle.

When the steam is delivered immediately into CC, the mismatching of the discharge capability of the engine flow path is mainly due to the constructions of the turbine and the compressor (there are no conditions for flow chocking in CC, although its hydraulic resistance can to a certain extent increase). Under these conditions, there exists a possibility that the compressor will fall in surge.

The mismatch between the discharge capability of the GTE relative to the air and the steam–gas mixture flowrates is eliminated in different ways. The most frequently used is an increase in the turbine passage section area.

In the CC of the GTE (see Fig. 1a), the steam generated in the HRB is further heated along lines *1''–2''–3a''* (see Fig. 1b). Line *1''–2''* represents the water delivery to the boiler via a feedwater pump, while line *2''– 3a''* represents water heating, evaporation, and partial superheating in the HRB tube bundles, which are performed without burning additional fuel. Temperature difference ΔT_{sh} is the difference between the steam temperature downstream of HRB and the steam–gas mixture temperature at the inlet to the HRB (at modern installations, not more than 40–50°C). The values of T_{ss} and π_c are determined as a result of optimization-type thermodynamic and technical-economic calculations. The cooling medium in the case under consideration is the atmosphere to which the steam–gas mixture from the HRB is discharged.

The use of the scheme considered does not allow complete utilization of the heat discharged to the atmosphere from the installation. The temperature of the steam–gas mixture at the outlet from the HRB is rather high, reaching 160–170°C. It is impossible to attain the lower temperature of the stack gases T_5 because the water equivalents (G_i, c_{pi}) of the water and the steam–gas mixture differ considerably and the compression ratio π_c in the cycle is high.

The main conclusion to be drawn from the analysis of the process performed is that, in CCIs with steam injection into a GTE, it is possible to obtain considerable specific capacities that are significantly higher than those in the original prototype, and this provides a low specific cost of the power installation. The results from the investigations conducted at the Salyut MMPP and the IVTRAN showed that the optimum value of π_c for a CCI with steam injection to the GTE is lower than that for a GTU operating by a simple cycle. This facilitates the use of the equipment of the prototype engine. In addition, the inclusion of the backpressure steam turbine in the thermal scheme of a CCI also reduces the optimum value of π_c. The use of this turbine makes it possible to raise steam parameters downstream of an HRB and provides an increase in the CCI thermal efficiency (see Figs. 1c and 1d) and its specific power. Even higher thermal efficiency can be obtained at CCIs with intermediate steam reheat in HRB (see Figs. 1e and 1f).

The efficiency of the power CCI with heat recovery is very sensible for operation of the turbine cooling system. When the aircraft engine is modernized with an account of the requirement that its lifetime should be considerably increased, the value of T_3 is reduced significantly (because of the long-term properties of the heat resistant materials used and the retention of the characteristics of the cooling systems of GTE articles). The transition to more effective steam cooling, however, makes it possible to retain the T_3 value at approximately the original level.

In their original (aviation) version, the aircraft engines to be reconstructed have no power turbines because their gas generator provides the working medium for the engine nozzle. The use of such engines in power-engineering installations suggests developing a free power turbine having high gas temperatures that would provide an increase in cycle efficiency. The principal possibility of operation of such a turbine at a temperature equal to or greater than T_3 gives a chance to obtain additional work in a CCI (see Figs. 1g and 1h, where $T_{3a'} < T_3 < T_{3c'}$). In so doing, proper optimization of all the parameters of the new cycle provides acceptable value of the thermal efficiency η_t.

It is apparent (and this is very important) that in the gas generator used in the thermal scheme shown in

Fig. 1g, the amount of reconstruction can be minimal. To reduce NO_x emissions, the existing CC is modernized to provide the possibility of injecting "environmental" steam. In this case, usually, there is no need to reconstruct the gas-generator turbine to meet condition (4). The main steam injection is done into an additional CC that is installed downstream of the gas generator. The optimization of the cycle consists of the provision of the maximum efficiency value. When this is done,

$$\eta_t = f(T_3; T_{3c'}; \pi_c, \pi_{t1}; \alpha; q_i), \quad (5)$$

where $T_{3c'}$ is the gas temperature upstream of the power turbine, π_{t1} is the expansion ratio in the gas-generator turbine, α is the air-excess coefficient in the gas-generator CC, and q_i is the fraction of steam in the steam–gas mixture downstream of the additional CC.

The functional dependence of η_t on α is determined by the existence of free oxygen in the mixture, i.e., the possibility of burning additional fuel. In addition, the parameters α, T_3, π_c, and π_{t1} determine lean and reach concentration limits regarding the flame propagation for different kinds of fuel.

An additional (but not universal) modernization of the scheme is shown in Fig. 1g. It consists of the use of a CCI with steam injection into a CC and an exhaust fan for stack gases (see Fig. 1i). In this CCI, the aircraft engine is used without considerable changes. This scheme is optimized as to its thermodynamic and technical-and-economic indices under certain conditions, the main one of which is the presence of a cold source (the cooler) and a high efficiency of the exhaust fan. The important factor is the pressure drop in the exhaust flow path from the power turbine to the exhaust fan. The heat-transfer surfaces of the HRB must provide heat recovery with acceptable boiler dimensions (the latter are increased to a certain extent due to HRB operation under rarefaction). An increase in the useful work performed by the CCI is achieved due to the use of a considerable additional pressure drop on the free power turbine π_{t2},

$$L = L_{\text{f.p.t}} - L_{\text{e.f}} - L_{\text{o.n}}, \quad (6)$$

where $L_{\text{f.p.t}}$ is the increase in the work done by the free power turbine against external forces (due to an increase in π_t), $L_{\text{e.f}}$ is work spent for driving the exhaust fan, and $L_{\text{o.n}}$ is the energy spent for own needs (for the cooler–condenser operation).

An increase in the useful work $L_{\text{f.p.t}}$ is a result of the overexpansion in the power turbine of the steam–gas mixture, which consists of steam and fuel combustion products, due to the presence of the exhaust fan,

$$L_{\text{f.p.t}} \sim G_{\text{d.g}}(1 + q_i c_{\text{pH}_2\text{O}}/c_{\text{d.g}})(T_{4a'} - T_{4'}),$$

where $G_{\text{d.g}}$ is the mass flowrate of dry gases at the power turbine inlet, $c_{p\text{H}_2\text{O}}$ and $c_{\text{d.g}}$ are the specific heats of steam and dry gases, and $T_{4a'}$ ($T_{4a''}$) and $T_{4'}$ ($T_{4''}$) are the temperatures of the exhaust gases (steam) at the outlet from the power turbine with or without the exhaust fan.

The mass flowrate of the steam at the inlet to the power turbine $G_{\Sigma\text{H}_2\text{O}}$ is the integral quantity, which includes the flowrates of the steam purposely delivered to the GTE, the steam contained in the air (determined by the original air humidity), and the "fuel" steam obtained in the course of fuel combustion. We should note that, due to a decrease in the gas temperature downstream of the power turbine, when the exhaust fan is switched on, the output of the HRB is decreased also, which to a some extent decreases $G_{\Sigma\text{H}_2\text{O}}$ and should be accounted for in the course of optimization of the installation as a whole.

The work spent for the exhaust fan drive is

$$\Delta L_{\text{f.p.t}} \sim G_{\text{d.g}}(1 + q_i c_{p,\,\text{H}_2\text{O}}/c_{\text{d.g}})(T_{7'} - T_{6'}),$$

where $T_{7'}$ and $T_{6'}$ are the gas temperatures at the outlet from and the inlet to the exhaust fan.

The amount of steam at the inlet to the exhaust fan $G_{\text{H}_2\text{O}}$ is determined from the conditions of steam condensation in the cooler–condenser (see Fig. 1i). Under certain conditions, all of the water delivered to the GTE can be condensed in this heat exchanger and, in addition, a certain amount of the "fuel" steam can be condensed as well. Therefore, in the exhaust fan, $G_{\text{H}_2\text{O}} \ll G_{\Sigma\text{H}_2\text{O}}$.

With the efficiencies of the exhaust fan and the turbine being approximately the same (a modernized GTE compressor can be used as an exhaust fan), relatively low temperature T_6, and $L_{\text{o.n}} = 0$, the value of ΔL will be positive. It is apparent that the work of the exhaust fan increases the stack temperature $T_{7'}$ of the installation. This favorably effects the natural draft of the stack gases' column and their dispersion in the atmosphere and protects the smoke stack against corrosion.

The results of the analysis of the thermodynamic schemes considered show the possibility of using a rather large spectrum of aircraft-engine derivative GTEs in power engineering. For example, at present in the Salyut MMPP, manufacturing a 20-MW gas turbines unit for power engineering has been mastered [1]. This unit operates with a simple Brayton cycle. The unit is manufactured on the basis of the AL-21 aircraft engine with minimum changes in its design and the addition of a free power turbine. The mass flowrate of the air at the inlet to the GTE compressor is $G_a \approx 100$ kg/s, and the thermal efficiency is $\eta_t = 0.35$. Presently, on the basis of the same prototype, a CCI with steam injection into the CC (according to the scheme shown in Fig. 1i but without a reburning combustion chamber and steam reheater) is being manufactured. With moderate parameters of the steam–gas mixture at the inlet to the turbine that drives the compressor (T_3 =1200°C) and some reduction of the air flowrate at

the compressor inlet down to $G_a \approx 87$ kg/s, a CCI power of 60 MW and thermal efficiency of $\eta_t = 0.49$ are provided. The installation of an additional reburning chamber in such a CCI and the use of the full output of the compressor ($G_a \approx 100$ kg/s) make it possible to create a CCI of 120-MW capacity.

Modernization of a diffusion-type CC to provide its operation in a CCI with steam injection usually requires changes in the fuel system and in the cooling system of CC liners; moreover, the CC must be equipped with devices for inputting the steam. The use of the steam considerably enhances the CC designer's possibilities: he not only can apply the working fluid that suppress NO_x formation, but he can control the distribution of the gas flows in the CC as well. In a CC without steam injection into the combustion zone, such a control of the gas flows is often provided by the use of a combustion chamber of variable geometry. This method is rather complex as regards design philosophy, is expensive, and is unreliable. It is significantly simpler, cheaper, and more reliable to use standard steam control valves for these purposes.

Steam injection changes the balance of the heat fluxes to the CC liner. In this case, the decisive factor is a change in the flame temperature and chemical composition. The requirement to reduce NO_x emission down to 50 mg/m^3 suggests the realization of a set of means that provide reduction of the flame temperature. In so doing, in the use in the primary zone of a low-toxicity CC the film cooling of the walls is undesirable. Heat transfer in this zone is determined by the characteristics of the flow at the burner and the primary-air nozzles outlets, as well as by the specifics of the arrangement of the burners.

The radiation heat flux depends on the flame temperature and its emissivity. With a change from a kerosene to a gaseous fuel (with other conditions, i.e., the hot gases' temperature, the pressure, and the geometric characteristics of the flame, being the same) the heat release from the aircraft-engine flame decreases. In the case of input of "environmental" steam, the gas temperature decreases. This considerably effects (reduces) the flame radiation also.

There is another difference in the design of the liner's wall of an aircraft-engine CC and its power-engineering derivative. It is connected with the application of heat-protection coatings on the inner surface of the liner. In the CCs of aircraft engines, such coatings are mainly used to protect the gas-collecting chamber. When the original engine is modernized, we should pay attention to the possibility of efficient use of the existing coating to protect the liner walls in the flame zone or even change the type of coating. In aircraft and marine CCs, enamel coatings are used that have been developed on the basis of different organic silicates having relatively high heat-conductivity coefficients (more than 0.5 W/(m K)). When modernizing CCs, it is expedient to use heat-barrier coatings on the zirconia basis, the heat conductance of which is lower, to protect the liner's walls.

Thus, the adoption of existing aircraft engines to the conditions of their operation in power systems as drives of electric generators (newly commissioned or used as substitutes whose lifetimes have expired) requires several conflicting problems to be solved. On the one hand, this adoption is justified in the economic sense only with a considerable increase in the specific capacity of the prototype engine while retaining the high efficiency reached in the latter. On the other hand, manufacturers are interested in the maximum retention of the engine design and the manufacturing technology used during the production of the engine to be adopted and in the minimum expenditures in the modernization of this technology. This problem is solved in the most rational way very efficiently by means of the use of aircraft engines in CCIs with steam injection into the combustion chamber. In so doing, a minimum amount of reconstruction work with the prototype engine is achieved by the use of the additional combustion chamber installed upstream of the high-temperature power turbine. The CC and the existing gas-generator turbine experience minimum changes, i.e., the fuel system is changed ("environmental" steam is injected). Steam delivery to a CC decreases NO_x emissions and creates favorable possibilities for controlling gas flows in the CC, thus promoting adaptation of one of the most complex elements of a GTE.

Further increase in the indexes of the installation can be achieved by the complication of the thermal scheme of a CCI with steam injection. In every concrete case, the advisability of using these measures should be substantiated by technical and economic calculations.

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